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doi:10.4028/www.scientific.net/KEM.651-653.458
Accepted: 2015-02-15

A parametric study on compression molding of reference parts with integrated features using carbon composite production waste

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Keywords: Thermoplastic, composite, production scrap, compression molding, integrated stiffener

Abstract. Compression molding of near net-shaped rib-stiffened plates has been performed for a parametric investigation on the filling behavior of chopped woven flake reinforcements. The experimental investigation showed that different aspect ratios of ribs can be filled completely within the tested maximum ratio of flake size to rib opening width of 6.25 and a maximum consolidation pressure of 15 bar. However, defects such as voids, non-impregnated regions and fiber matrix separation may arise depending on the combination of parameters and a mechanical jamming effect caused by the woven architecture of the flakes. A tendency for a limiting consolidation pressure is observed based on the fiber matrix separation. The ability to re-use thermoplastic prepreg cutting waste has been demonstrated.

Introduction

In the past few decades the use of high performance thermoplastic composites in aerospace industry has risen to a considerable amount. However, parts with complex geometries are produced as separate components to be assembled in subsequent process steps. This can be attributed primarily to the lack of formability caused by highly stiff and inextensible reinforcing fibers. Integrating design features such as ribs, thickness transitions, and the ability to form near net-shaped parts with minimal post processing are challenging to be achieved with continuously reinforced composites. On the other hand, use of discontinuously reinforced composites can fill this gap in combination with suitable processing method enables the production of complex geometries in one shot. Compression molding compounds[1] such as BMC, SMC, are among the existing discontinuous composite materials based on thermosets whereas LFT and GMT are based on thermoplastics. A relatively new class of molding compounds called CPMC is available as both variants. Most of them use chopped fibers or chopped unidirectional tapes of a certain length as reinforcements.

In this study chopped woven prepreg material is used as unit reinforcing elements, henceforth referred to as flakes, with the advantage of providing a two dimensional (2D) reinforcing effect. It is worthwhile to note that the process scrap from the conventional thermoplastic prepreg cutting process can be used as a source for producing the chopped woven flakes. Therefore, this method provides a two-fold advantage of using discontinuous 2D reinforcements to mold integrated design features and the ability to use the recyclate from conventional composite manufacturing processes.

During processing of the discontinuous molding compounds, the initial material loading pattern and the mold geometry dictates if there will be macroscopic flow of the material. The reinforcements move along with the mesoscopic flow of the matrix to fill the intricate parts of the mold cavity. In this process of filling, the reinforcements get reoriented and there is a possibility of fiber-matrix separation due to the change in resistance to the material flow created by the mold geometry. The usual molding procedure is to close the mold at a higher rate to expel the air in the

[1] BMC: bulk molding compounds, SMC, Sheet molding compounds, LFT: Long fiber thermoplastic, GMT: Glass mat thermoplastic, CPMC: Chopped prepreg molding compound.

molding compound and to move reinforcements as far as possible to the entire cavity. It is then followed by a smaller rate of closure until the consolidation pressure is reached, to provide time for filling the mold and for consolidation [1].

Unlike flat plates, the flow is influenced by geometric features and generally is more complicated. For instance in the case of ribs, there can be loss of pressure in the entrance region. Additionally, the fiber structure can act as a filter causing the matrix to get separated based on the entrance geometry (rib width, flange thickness, lead in radius). The material parameter, in this case the reinforcement size, adds to the above effects making the flow more non-uniform and thus creating a matrix rich rib. This leads to a performance reduction as well as secondary effects such as sink marks and uneven surfaces.

A good proportion of study has been done in the past on the flow of anisotropic material in flat sections [2-6] and non-flat sections [7-9] with materials such as SMC and GMT which contains primarily fiber filaments or bundles suspended in polymer matrix. However, only a few have experimentally characterized the effect of fiber matrix separation in flat sections using GMT [10] and in non-flat sections such as ribs using SMC [7]. In [7], the authors have developed a model dimensional analysis based on rib dimensions in which the results show that for a larger rib opening, the resistance to flow into the rib decreases, whereas the pressure loss occurring at the entrance due to sudden change in section will cause fiber-matrix separation. In [10], the experimental results show that the mold closing rate has an influence on the observed non-homogeneity of fiber volume fraction across the flat section. Although these flow filling studies have been done for fiber bundle reinforced molding compounds such as the materials mentioned above, the process of filling flaky woven reinforcements into and across non-flat regions has not been explored so far in the literature.

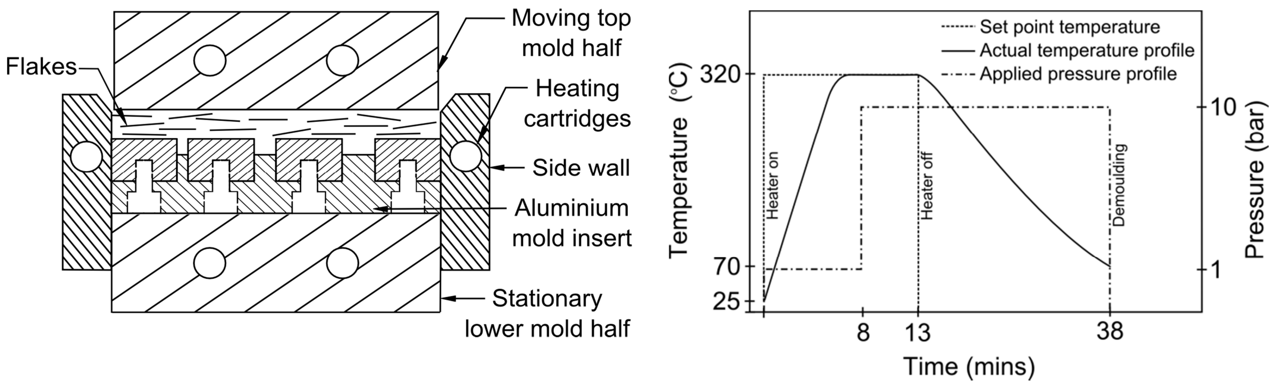
This article focusses on one of the typical non-flat design features, namely integrated stiffeners or ribs, which are commonly added to increase the flexural stiffness of the component. The objective of this study is to experimentally investigate and understand the effect of design, bulk material and process parameters on the quality of the molded part. A flat plate with ribs of different aspect ratios is molded with two different flake sizes under three different consolidation pressures. The consolidation quality is assessed with void content measurements and fiber matrix separation analysis using optical microscopy and image analysis. The following sections elucidate the materials, methods and the choice of parameters investigated in this study and its effects on the filling behavior, subsequently followed by a brief discussion and conclusions.

Experimental Method

Material and Equipment. The material used in this study is cutting waste of Cetex® Carbon/Polyphenylenesulphide (C/PPS) semi-preg[2] with a 5 harness satin (5HS) weave from TenCate Advanced Composites. The thickness of the layer is 0.31 mm and the fiber volume fraction (V_f) of the material is 50%. The nominal processing temperature is 320 ^{o}C and the polymer has a glass transition temperature (T_g) of 90 ^{o}C. A consolidation pressure of 10 bar is specified for producing laminates from these semi-preg material. The semi-pregs are chopped in to squares of side length 5 mm and 12.5 mm. The choice of the planar aspect ratio of one is to maintain a constant unit fiber length in both primary directions of the chopped flakes.

An instrumented compression molding setup, as shown in Figure 1(a), is used in this study to mold the scaled integrated features from chopped woven flakes. The setup consists of a moving half which is fixed to the crosshead of a universal testing machine while the lower half of the press is fixed to the stationary frame of the machine. Removable side walls are attached to the lower half to contain the mold insert and form the mold cavity. Heating cartridges are used to heat the mold halves and side walls in conjunction with PID controllers and thermocouples in the mold halves. A laser speckle extensometer is used to measure the instantaneous mold separation.

[2] In semi-pregs, the reinforcing carbon fabric is either spray coated with polymer matrix on both sides or laminated with films of polymer matrix and hence is partially pre-impregnated with matrix.



(a) (b)

Figure 1: (a) Sectional view of the molding setup with the modular aluminium insert in place and cavity filled with flakes. (b) Typical process cycle.

The force exerted on the mold, displacement and temperature of the mold halves are recorded using a data acquisition system. A modular mold insert with rib cavities was utilized to mold the rib-stiffened plates. Figure 1(a) shows the sectional view of the mold with an aluminium insert containing three different rib cavities (width x depth) of 2x3, 4x3, 6x3 mm respectively from left. A minimal entrance radius (i.e. corner radius between plate and rib) of around 0.25 mm is present due to manufacturing limits. The molding area finally has a dimension of 60 mm x 60 mm.

Manufacturing. The final plate thickness in the flat section is intended to be 2 mm. A calculated amount of 15 grams of chopped flakes are filled in the mold cavity randomly and the mold is closed to one bar pressure gradually. Polyimide (PI) foil is used on the sides to avoid any spillover of the flakes, since the bulk factor of the flakes is larger than the molded plate. Figure 1(a) shows the mold filled with chopped woven flakes and PI foils in the sides. The mold is then heated to the molding temperature of 320 ^{o}C and subsequently closed with a specified closing rate, until it reaches the required consolidation pressure. A force feedback control is used to hold a constant consolidation pressure. Figure 1(b) shows a typical molding cycle used in this study. A consolidation dwell of five minutes is set before the heaters are switched off for all the experiments. Figure 2(b,c) shows both sides of the demolded part with ribs. It can be noted that the front side shows signs of sink marks along the location of ribs as well as interrupted flake orientation compared to the rest of the plate.

Experimental Design and Characterization Method. The parameter space concerning the given material (V_f, flake size, flake thickness) and process (closing rate of the mold, consolidation pressure, temperature) together spans a vast area. In this preliminary study the flake size and consolidation pressure, which are amongst the important factors influencing the final quality of the part were considered as variables. The rate of closure of the mold and processing temperature were considered as fixed parameters. A previous study on the squeeze flow of the chopped woven materials [6] has shown that for the flake sizes considered in this study, a closing rate of 2 mm/s resulted in minimal mechanical jamming of flakes due to the stacking of flakes. The flake sizes of

(a) (b) (c)

Figure 2: (a) Mold filled with 12.5 mm flakes, (b) front side of the molded plate after demolding (60 x 60 x 2 mm), (c) rib side of the plate after de-flashing and removal of PI foils from the sides.

5 mm and 12.5 mm were chosen based on the smallest unit cell dimension of the woven architecture (5HS) as well as to minimize the size effect considering the dimensions of the mold. The consolidation pressure and temperature was chosen based on the nominal process specification of the C/PPS material in combination with the maximum pressures observed in the squeeze flow tests under the chosen processing temperature. The different consolidation pressures chosen are 5, 10 and 15 bar. All the experiments were performed at a mold closing rate of 2 mm/s and with a molding temperature of 320 ^{o}C. In addition to the rib-stiffened plates, a set of reference flat plates were also molded with the same process conditions to provide a datum for comparison.

Characterization of Consolidation Quality. Optical micrographs were prepared for different sections of the molded part to characterize the ability of the material to fill the ribs under the range of consolidation pressures investigated. The defects such as voids, non-impregnated regions, and matrix pockets caused due to fiber matrix separation in the rib sections were measured using image analysis with the software ImageJ.

Results and Discussion

Rib Filling. Figure 3(a-f) shows typical bright field optical micrographs of the rib cross sections molded with different flake sizes and consolidation pressures. The black regions are carbon fiber bundles and the white regions are pockets of PPS matrix. It can be noted that under the investigated range of pressures and flake sizes, all the ribs are completely filled with the molding material. However, the proportion of fiber and matrix is different which is strongly influenced by the chosen combination of parameters.

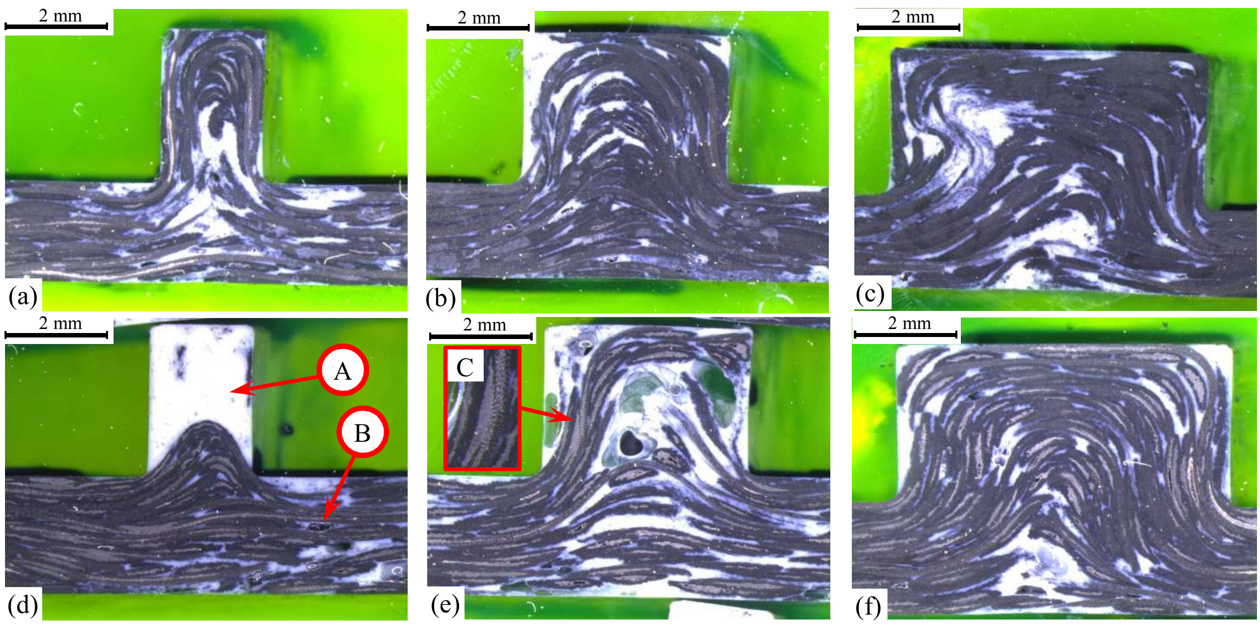


Figure 3: Micrographs of rib sections with different molding parameter combinations. Refer Table 1 for combinations used (rib width, flake size, consolidation pressure) in (a)–(f). A: Fiber-matrix separation, B: Voids, C: Non-impregnated regions.

The top row of micrographs shows ribs molded with a flake size of 5 mm. It can be observed that in (a), 5 bar pressure is sufficient to fill the 2 mm wide rib. Nevertheless, the presence of voids and non-impregnated regions visible as gray spots in the core of the fiber bundles (also depicted as C in (e)) suggests a poor consolidation quality. In the case of 12.5 mm flake size for the same 2 mm wide rib (d), severe fiber-matrix separation occurs. The flakes have to be deformed and pushed into the rib for which the 5 bar consolidation pressure was apparently not sufficient. Conversely, the flakes bridged the rib opening giving rise to an interstitial pressure gradient in the matrix, similar to a condition under squeeze flow in [10], causing the matrix to percolate into the rib. The case of 4 mm wide ribs consolidated under 10 bar pressure is shown in Figure 3(b,e) with 5 mm and 12.5 mm flake size respectively. The filling of the latter is mostly disturbed with void formation at

Table 1 Respective parameter combinations used for molding the sections shown in Figure 3.

Micrographs in Figure 3	Rib width [mm]	Flake size [mm]	Consolidation pressure [bar]
a, b, c	2, 4, 6	5	5, 10, 15
d, e, f	2, 4, 6	12.5	5, 10, 15

the entrance and in the corners. Similarly, the widest rib and the largest flake size combination requires 15 bar pressure to get completely filled as shown in (f) but with voids and non-impregnated regions.

These consolidation defects show that the pressure at the rib section is below the average applied pressure. One of the causes might be due to the formation of the mechanically jammed spots where the number of flakes in the through thickness direction is larger than the average number. This causes a direct load transfer to the lower mold half due to incompressibility of the fiber bed and leads to an uneven pressure distribution in the adjacent regions. Therefore, a trade-off exists between the filling and consolidation quality. From the filling point of view, the chosen parameter combination is sufficient to fill the ribs completely, but from the consolidation standpoint, for the chosen fixed parameters, a higher consolidation pressure above 15 bar will be helpful to reduce the void content and increase the impregnation level considering the presence of local mechanically jammed regions.

Quantitative Characterization. By means of thresholding and binarization of dark field optical micrographs of the polished rib sections, area fractions of typical defects are estimated and are plotted in Figure 4 and Figure 5. Figure 4(a) shows the void fraction present in the matrix phase for different rib sections and reference flat plate, for the flake sizes used for molding. For the case of 4 mm rib width, it can be observed that as the consolidation pressure increases, the void content reduces consistently for 12.5 mm flakes. For the 5 mm flakes, void content tends to slightly increase due to the disturbance generated in the flow as a result of higher pressure in the entrance region. For both flakes sizes considered, the area fraction of non-impregnated regions reduces with increasing consolidation pressure. However the absolute values are much smaller in the case of 5 mm flakes. As the flake size gets smaller the material gets less non-homogenous which correlates with the reduced voids and non-impregnated regions in the case of smaller flakes.

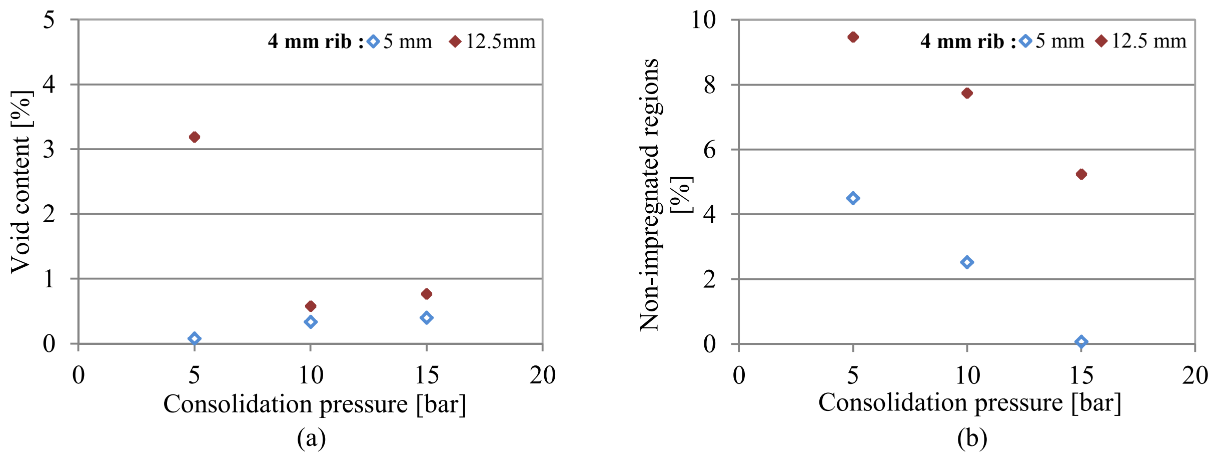


Figure 4: Percentage defect in the rib section including the rib entrance region. (a) Voids, (b) Non-impregnated region.

Fiber matrix separation as mentioned in the previous section manifests itself as pockets of matrix between the fiber bundles visible in the rib sections. As it can be seen in Figure 5 that there exists an optimum consolidation pressure to obtain minimal separation of matrix. However, the effect is larger for smaller flakes where the matrix has a tendency to percolate and accumulate in the corners of the rib and in the rib entrance due to abrupt changes in pressure gradient.

For a fixed flake size and a rib opening, the filling quality can be observed to improve with the increase in consolidation pressure, however, beyond a limiting pressure the fiber matrix separation has a non-monotonic behavior. Consequently, the difference in fiber volume fraction between the rib and flange section becomes large which in turn affects the mechanical performance of the part.

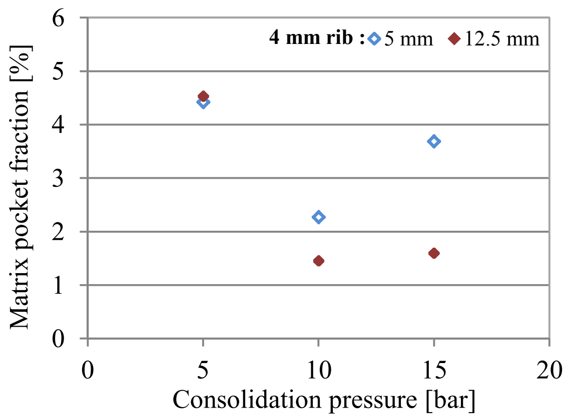


Figure 5: Percentage defect (matrix pocket) in the rib section including the rib entrance region.

Conclusions and Future Work

An experimental investigation on the compression molding of rib stiffened plates with chopped woven reinforcements has been presented. The recyclate from conventional thermoplastic prepreg cutting waste was used to manufacture the flake reinforced near net-shaped part. The filling behavior with different combinations of design, material and process parameters have been analyzed and discussed qualitatively and quantitatively. The results show that for high quality parts with a specific flake size and rib opening combination, the choice of the consolidation pressure is essential for obtaining proper impregnation and low void content. At the same time, the consolidation pressure should be bounded for limiting excessive fiber matrix separation.

In the future, the knowledge gained from this experimental investigation will be the basis for the development of semi-analytical process models considering a meso-scale flow and a pseudo random arrangement of flakes, valid for both flat as well as ribbed sections. The solution will be validated with experimental results obtained in this study.

Acknowledgements

This project is funded by and executed at the ThermoPlastic Composites Research Center (TPRC). The support of the Region Twente and the Gelderland & Overijssel team for the TPRC, by means of the GO Program EFRO 2007-2015, is gratefully acknowledged.

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